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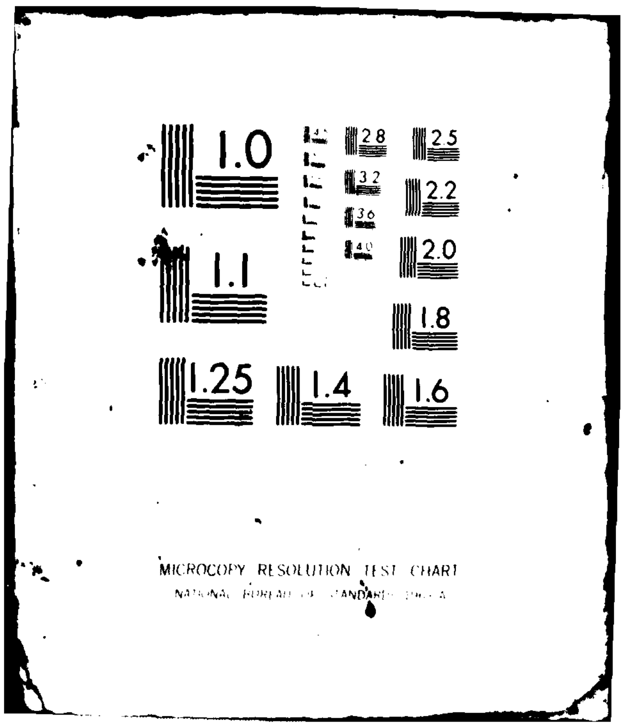
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MINIMUM WEIGHT DESIGN OF FLAT SANDWICH PANELS UNDER EDGEWISE COMPRESSION LOADS

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Dayton, Ohio 45469

March 1981

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An approach to the optimum design of flat, rectangular sandwich panels subjected to edgewise compression loading has been developed. Using a nonlinear programming method called the Sequential Unconstrained Minimization Technique, the design parameters characteristic of sandwich construction are determined so that the final panel configuration is not just an acceptable design, but is the best acceptable design as far as total panel

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weight is concerned. The design parameters are the individual thicknesses of the top and bottom face sheets and of the core, the cell size and foil thickness of honeycomb core, and the density of foam core. The acceptable ranges of the design paramerers are limited by constraints which ensure, for example, that the thicknesses are within minimum and maximum limits, that the faces do not yield, wrinkle, or dimple, and that the panel does not buckle. Possible panel loads are edgewise compression in two directions.

The computer program which implements the minimum weight sandwich panel design procedure is an easy to use interactive code. Data are entered by the user in response to self-explanatory prompts from the program. The user is offered the opportunity to change data before the optimization procedure is initiated. The results of the minimum weight computations are presented to the user within a few seconds in a concise yet informative format. Typical output data include the optimum values of the design variables, the minimized panel weight, and final values of the design variable constraints.

FOREWORD

This report describes work performed by the University of Dayton Research Institute (UDRI) under Air Force Contract F33615-77-C-3075, Structural Sandwich Composites. The effort was conducted for the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, under the administration and technical direction of Air Force Project Engineer, Mr. Harold C. Croop (AFWAL/FIBCB).

Administrative project supervision at the UDRI was provided by Mr. Dale H. Whitford (Supervisor, Aerospace Mechanics Division), and technical supervision was provided by Dr. Fred K. Bogner (Group Leader, Analytical Mechanics Group).

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1
INTRODUCTION

Structural sandwich composites form a very important part of the total materials pool available to structural designers. The high strength-to-weight ratio which is characteristic of structural composites often gives them a favorable position over more conventional materials for structural applications for which weight is a limiting or controlling factor in the material selection. Consequently, structural sandwich composites are used widely for various applications; in particular, they are especially valuable for aerospace applications due to their high strength and low weight traits.

Since structural sandwich composites are used in many structures for which low weight is a desirable property, they are natural candidates for application of mathematical optimum design techniques. The consideration of sandwich in minimum weight design studies offers greater challenge and wider opportunity for significant weight reduction, because additional design parameters are available for adjustment by the structural designer. For example, in addition to the normal design parameters such as panel thickness and material, the designer of sandwich panels can choose the thickness of individual faces, the thickness of the core, the type of core, the core material, as well as parameters which control the density of the core.

Although the availability of numerous design variables offers the creative designer opportunities which would not normally exist, the process of optimum design of sandwich is necessarily more complex. The purpose of this report is to present an approach to the minimum weight design of sandwich panels. Section 1 defines the scope of the study, and presents a body of literature concerned with the design of structural sandwich composites. Section 2 is concerned with a development of the mathematical representation of the problem of the minimum weight design of sandwich panels. The general constrained minimization technique used is discussed. Also, the mathematical representation of the sandwich design parameters, weight, and design constraints within the framework of the selected optimization procedure are presented. A description of the computer program which was developed to implement the sandwich panel minimum weight design procedure is presented in Section 3. Instructions for operation of the interactive program are given, and typical applications of the program to representative design examples are considered. Section 4 concludes that the results obtained in this panel optimization study are very encouraging, and recommends that efforts be undertaken to apply minimization techniques to more general structures which contain sandwich.

1.1 SCOPE

This report is concerned with the automated minimum weight design of flat, rectangular, sandwich panels subjected to edgewise compression loads (Paragraph 2.3 gives a more complete description of the particular geometrical, material, and loading configurations considered). The rather narrow problem scope was selected as a basis for demonstrating that application of mathematical constrained optimization techniques to the design of sandwich construction is both feasible and practical. The sandwich panel design problem considered contains all of the basic ingredients of a more complex problem for which sandwich panels are only individual components. That is, design parameters and design parameter constraints are used which are not normally considered in more conventional designs. It is recommended in Section 4 that further work is warranted in combining the advantages of mathematical programming approaches in individual panel design (this study), with the optimality design techniques used for overall design of more extensive structures which contain panels as individual components.

1.2 LITERATURE

Quite a large body of literature exists concerning the general topic of optimum structural design and the more specific subject of optimum sandwich composites design. A complete review of the pertinent literature is not attempted here. Instead we merely provide a bibliography of sources (Appendix A) which pertain to the subject. The bibliographic list has been compiled from the Structural Sandwich Composites Bibliography of Reference 1.

SECTION 2
TECHNICAL APPROACH

This section presents the mathematical basis for the computer program described in Section 3. The sandwich optimization study considered in this report is put into the general framework of a general constrained optimization problem (Paragraph 2.1), and solutions are obtained using an approach called the sequential unconstrained minimization technique (Paragraph 2.2). The particular geometry, material, and loading of the sandwich panel studied are defined in Paragraph 2.3, and the parameters chosen for performing optimization studies are defined in Paragraph 2.4. The equations which quantify the objective function (weight in this study) and the constraints on the design parameters are given in Paragraphs 2.5 and 2.6.

2.1 GENERAL CONSTRAINED OPTIMIZATION PROBLEM

The constrained optimization approach has been selected for this sandwich panel optimization study. A complete account of this method is found in References 2 and 3. A brief description of constrained optimization is presented here for completeness.

A statement of a constrained optimization problem in mathematical terms is:

> Select design parameters $d_1,\ldots,d_n$ such that an objective function $W(d_1,\ldots,d_n)$ is minimized, subject to the inequality design parameter constraint functions, $g_i(d_1,\ldots,d_n) \geq 0$, $i = 1,\ldots,N$, and the equality design parameter constraints, $H_i(d_1,\ldots,d_n) = 0$, $i = 1,\ldots,M$. (2.1)

In physical terms, the n design parameters $d_1,\ldots,d_n$ can be viewed as the axes of an n-dimensional, orthogonal coordinate space on which the objective function $W(d_1,\ldots,d_n)$ is defined. Each point of this n-dimensional space represents a possible set of design parameters. The constraint functions serve to divide the total design parameter space into acceptable and unacceptable regions as far as valid designs are concerned. Then the optimization problem can be visualized as the selection of that point in the acceptable region of the design space which corresponds to the minimum value of the objective function.

There are essentially two general approaches which can be used to solve the optimization problem stated above; these basic techniques are known as direct methods and indirect methods. The direct methods employ a function minimization scheme which operates directly on the objective function, with the constraints being considered as limiting surfaces. Specialized techniques have been developed for determining whether an optimum has been attained upon encountering constraints and for proceeding with the optimization if necessary. The indirect methods, on the other hand, rely on a reformulation of the problem which converts the constrained optimization problem into an unconstrained optimization problem. This is an extremely attractive approach since it means that standard, well established unconstrained minimization techniques can be used to obtain an optimum design.

The indirect approach has been chosen for the optimization of sandwich panels reported here. In particular, the Sequential Unconstrained Minimization Technique developed by Fiacco and McCormick has been used to obtain the set of design parameters which yield an optimum weight sandwich component. This method is described briefly in the following paragraph.

2.2 SEQUENTIAL UNCONSTRAINED MINIMIZATION TECHNIQUE

The Sequential Unconstrained Minimization Technique (SUMT) has been chosen due to its proven applicability combined with the fact that it is simple and relatively foolproof to use. The mathematical theory behind this method is contained in Reference 4 while examples of the application of the technique to various optimization problems are given in Reference 5. The particular form of the SUMT which is used generates intermediate designs which all lie inside the acceptable region of the design space.

The basic idea behind the SUMT is relatively simple. In this approach the objective function is augmented with a "penalty function" which is designed to contain the effects of the design constraints. Then a sequence of unconstrained minimizations is performed on the new functions, with each successive minimization producing a result which is closer to the true optimum.

In equation form, the SUMT objective function is

$$\Phi(r;d_1,\ldots,d_n) = W(d_1,\ldots,d_n) - r\sum_{i=1}^{N} \ln g_i(d_1,\ldots,d_n)$$

$$+ \sum_{i=1}^{M} \frac{H_i^2(d_1,\ldots,d_n)}{r} \tag{2.2}$$

where r is a parameter which controls the magnitude of the penalty function (the last two terms in Equation 2.2); if $r = 0$ then $\Phi = W$. The general idea behind the SUMT is to select a value for r, perform a minimization, reduce r, perform another minimization, etc., until r is made sufficiently small that $\min \Phi \approx \min W$. References 2, 4, and 5 contain more complete discussions of the theory of this method.

The following algorithm has been used in applying the Sequential Unconstrained Minimization Technique to an optimization problem (refer to Figure 1):

(a) Pick a starting value for r and select an initial set of design parameters $(d_1,\ldots,d_n)_0$ satisfying all the constraints (Equation 2.3).

(b) Minimize Φ (Equation 2.2) to obtain $(d_1,\ldots,d_n)_M$, where M denotes the Mth pass through the algorithm.

(c) Check for convergence to the optimum.

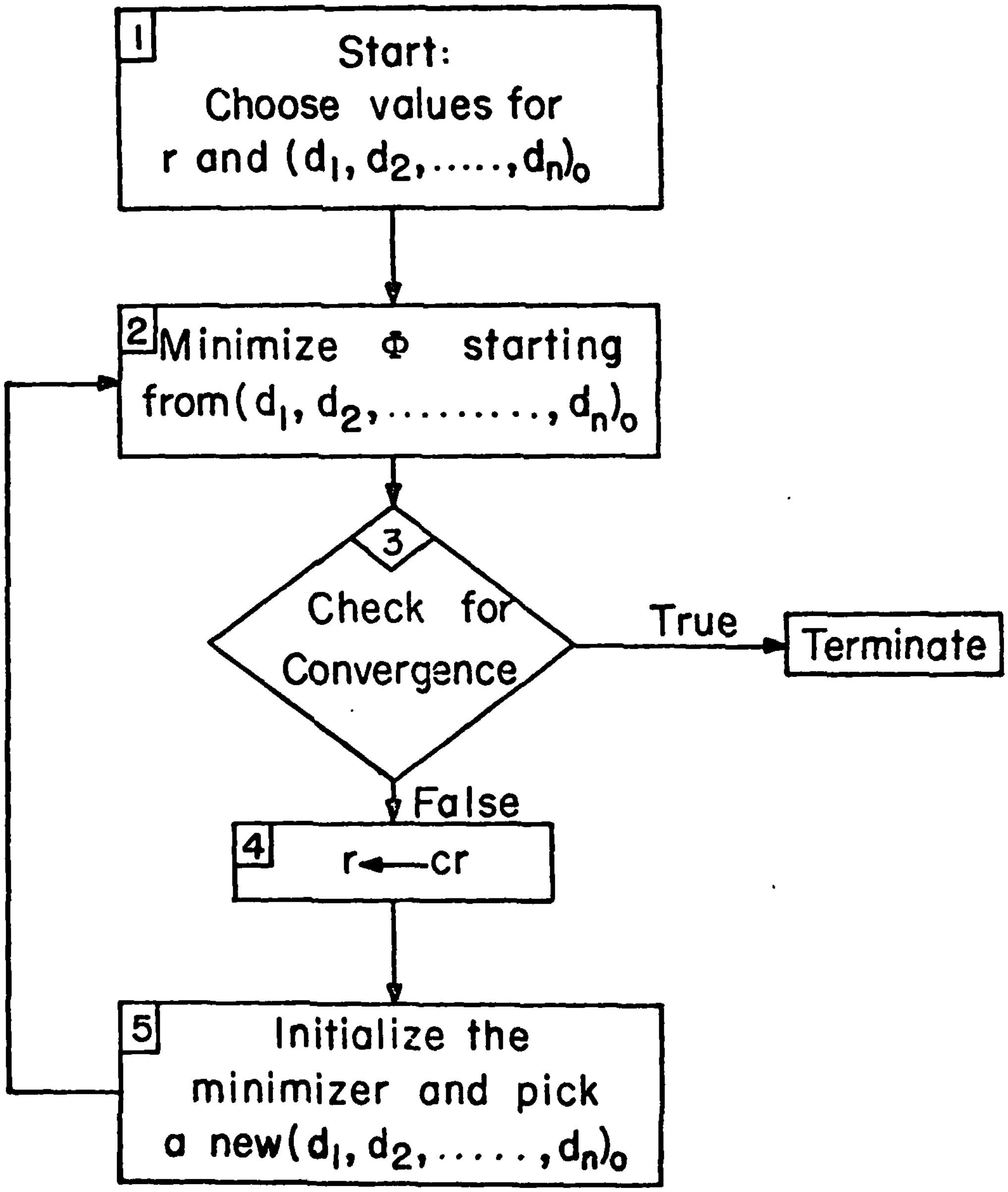

Figure 1. SUMT Logic Diagram.

(d) If the convergence criterion is not met, reduce r by $r \leftarrow cr$, where $c < 1$.

(e) Compute a new starting point for the minimization, initialize the minimization algorithm, and repeat from Step 1.

2.3 STRUCTURE AND LOADING

The class of structure and loading considered for this initial sandwich optimization study is that represented in Chapter 5 of the MIL-HDBK-23A.[6] In particular, the reported study is directed at simply-supported, rectangular, three layer, sandwich plates subjected to inplane compression loads.

The geometry of the subject sandwich plates is shown in Figure 2. The planform dimensions are denoted by a and b. The two face plates are of uniform but different thicknesses t_1 and t_2, and the core has uniform thickness t_c. The total thickness of the sandwich is taken as the sum of the three layer thicknesses $d = t_1 + t_2 + t_c$, assuming that the bonding material has zero thickness.

The faces are assumed to be conventional thin plates with orthotropic material properties denoted by E_{ix}, E_{iy}, G_{ixy}, ν_{ixy}, ν_{iyx}; however, computations are based on effective compressive moduli defined by $E_i' = \sqrt{E_{ix} E_{iy}}$. The core is assumed to have no inplane stiffness at all; however, the transverse shear moduli are represented by G_{cxz} and G_{cyz}, and the transverse elastic modulus is given by E_{cz}.

The permissible loadings consist of uniform inplane compression loads as shown in Figure 3. A single load condition can consist of a uniform load $\tilde{N}_x$ compressing the panel in the x-direction, or a uniform load $\tilde{N}_y$ compressing the panel in the y-direction.

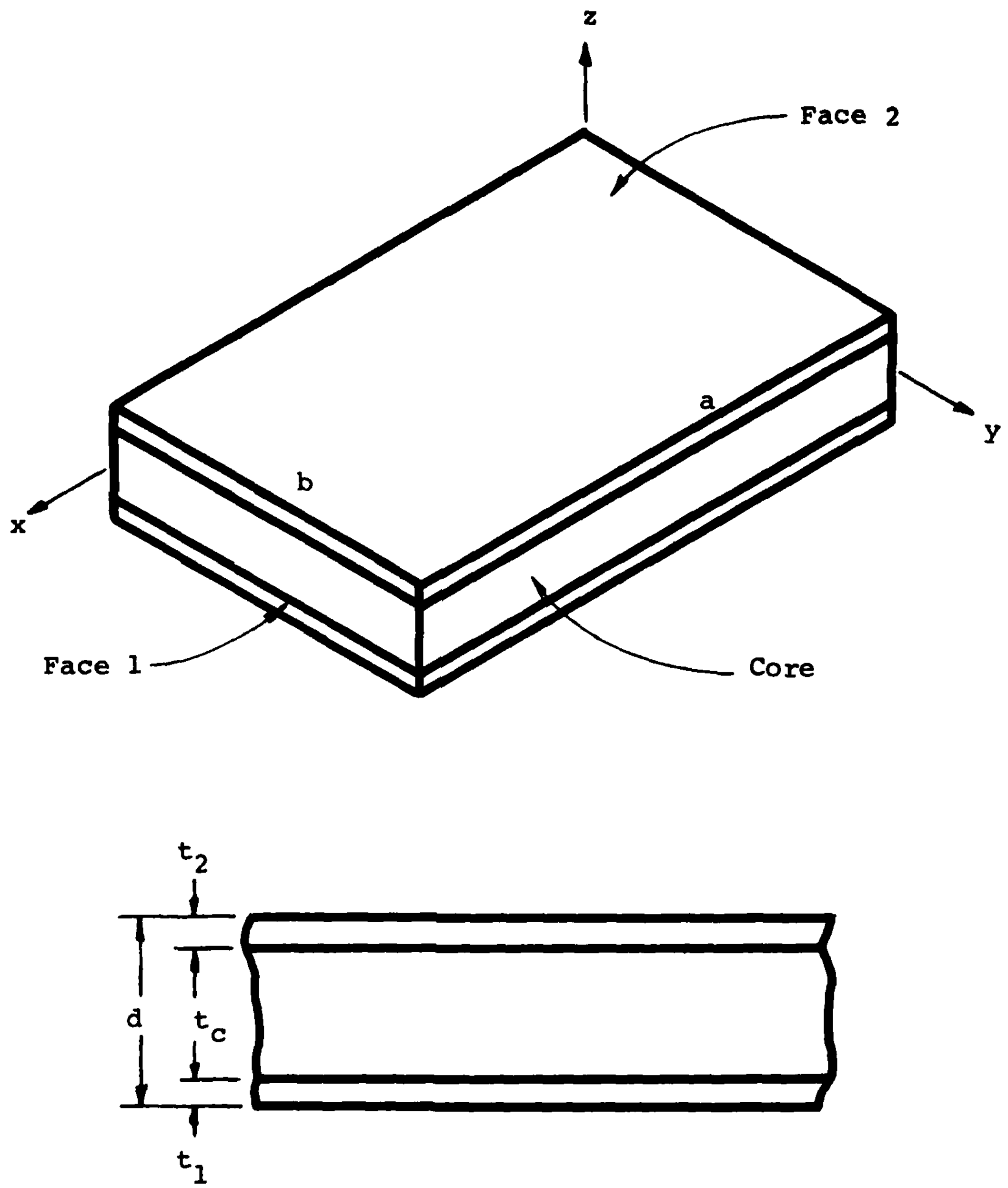

Figure 2. Sandwich Panel Geometry.

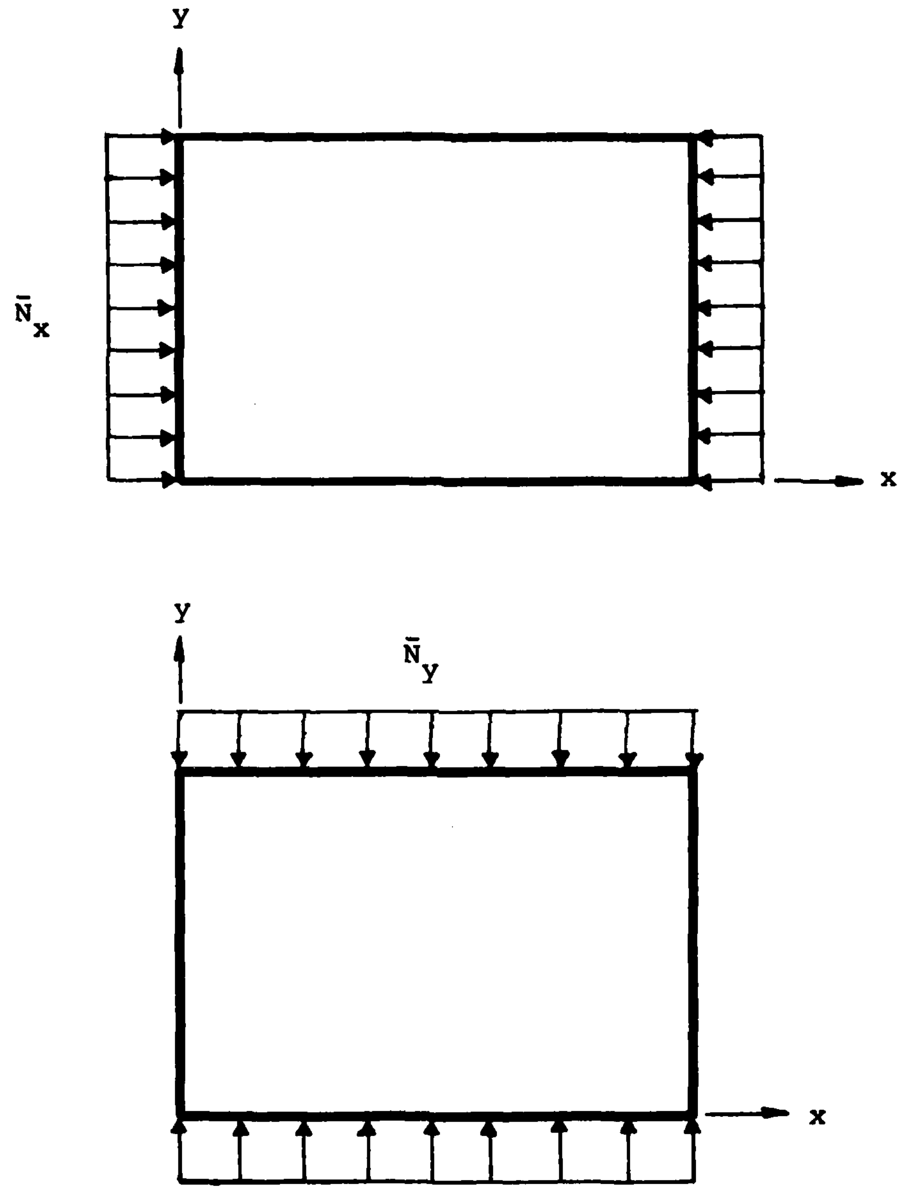

Figure 3. Panel Loading.

2.4 SANDWICH PANEL DESIGN PARAMETERS

For the purpose of this sandwich panel optimization study it is assumed that the planform dimensions of the panel and the material of the faces and core are predetermined. The design parameters $d_1,\ldots,d_n$ of Equation 2.1 consist of the thicknesses of the constituent parts of the sandwich panel together with parameters that control the density of the core depending on the type of core used - either honeycomb or foam.

For the design of sandwich panels having honeycomb core there are five possible design parameters:

1. Face 1 thickness, t_1
2. Face 2 thickness, t_2
3. Core thickness, t_c
4. Honeycomb cell size, s
5. Honeycomb foil thickness, t_f

In the case of foam core sandwich four design parameters are available:

1. Face 1 thickness, t_1
2. Face 2 thickness, t_2
3. Core thickness, t_c
4. Core density, p_c

The various possible design parameters noted above can be selected in any numbers and combinations.

2.5 SANDWICH PANEL MERIT FUNCTIONS

The merit or objective function $W(d_1,\ldots,d_n)$ of Equation 2.1 has been taken to be the total weight of a sandwich panel. The bonding material weight will be approximately constant for a panel of specified planform dimensions regardless of the particular values of the design parameters; therefore, the weight of the bonding agent has been excluded from the panel weight W.

The expressions for the objective function for particular types of core materials are:

1. Hexagonal Cell Honeycomb Core

$$W(t_1,t_2,t_c,s,t_f) = (\rho_1 t_1 + \rho_2 t_2 + \frac{8t_f\rho_f}{3s} t_c)A \tag{2.3a}$$

2. Square Cell Honeycomb Core

$$W(t_1,t_2,t_c,s,t_f) = (\rho_1 t_1 + \rho_2 t_2 + \frac{2t_f\rho_f}{s} t_c)A \tag{2.3b}$$

3. Foam Core

$$W(t_1,t_2,t_c,p_c) = (\rho_1 t_1 + \rho_2 t_2 + \rho_c t_c)A \tag{2.3c}$$

The design parameters have been defined in the previous paragraph. The face and honeycomb material densities ρ_1, ρ_2, and ρ_f are considered to be predetermined quantities, as is the panel planform area A.

2.6 SANDWICH PANEL DESIGN PARAMETER CONSTRAINTS

To make the minimum weight design of sandwich panels more realistic, numerous design parameter constraints are imposed. All of the constraints are of the inequality type ($N > 0$, $M = 0$ in Equation 2.1).

The particular inequality constraints $g_i \geq 0$, $i = 1,\ldots,N$ imposed on the design parameters of Paragraph 2.4 are given below. Each constraint is designed so that if it is close to being violated, then the constraint value will be a small positive number.

1. Minimum Face 1 Thickness

$$g_1 = \frac{t_1}{t_{1min}} - 1 \tag{2.4}$$

2. Minimum Face 2 Thickness

$$g_2 = \frac{t_2}{t_{2min}} - 1 \tag{2.5}$$

3. Maximum Sandwich Thickness

$$g_3 = 1 - \frac{t_1 + t_2 + t_c}{d_{max}} \tag{2.6}$$

4. Minimum Core Thickness

$$g_4 = \frac{t_c}{t_{cmin}} - 1 \tag{2.7}$$

5. Minimum Honeycomb Foil Thickness

$$g_5 = \frac{t_f}{t_{fmin}} - 1 \tag{2.8}$$

6. Minimum Honeycomb Cell Size

$$g_6 = \frac{s}{s_{min}} - 1 \tag{2.9}$$

7. Minimum Foam Core Density

$$g_7 = \frac{p_c}{p_{cmin}} - 1 \tag{2.10}$$

8. Maximum Honeycomb Cell Size

$$g_8 = \frac{s_{max}}{s} - 1 \tag{2.11}$$

9. Compressive Yield of Face 1

$$g_9 = 1 - \frac{\bar{N}\, E_1'/(t_1E_1' + t_2E_2')}{F_1} \tag{2.12}$$

10. Compressive Yield of Face 2

$$g_{10} = 1 - \frac{\bar{N}\ E_2'/(t_1E_1' + t_2E_2')}{F_2} \qquad (2.13)$$

11. Wrinkling of Face 1 - Honeycomb Core

$$g_{11} = 1 - \frac{\bar{N}\ E_1'/(t_1E_1' + t_2E_2')}{(F_{1w})_{hc}} \qquad (2.14)$$

where,

$(F_{1w})_{hc}$ = (Equation 3:6, Reference 6)

12. Wrinkling of Face 2 - Honeycomb Core

$$g_{12} = 1 - \frac{\bar{N}\ E_2'/(t_1E_1' + t_2E_2')}{(F_{2w})_{hc}} \qquad (2.15)$$

where,

$(F_{2w})_{hc}$ = (Equation 3:6, Reference 6)

13. Wrinkling of Face 1 - Foam Core

$$g_{13} = 1 - \frac{\bar{N}\ E_1'/(t_1E_1' + t_2E_2')}{(F_{1w})_{foam}} \qquad (2.16)$$

where,

$(F_{1w})_{foam}$ = (Equation 3:1, Reference 6)

14. Wrinkling of Face 2 - Foam Core

$$g_{14} = 1 - \frac{\bar{N}\ E_2'/(t_1E_1' + t_2E_2')}{(F_{2w})_{foam}} \qquad (2.17)$$

15. Dimpling of Face 1 - Honeycomb Core

$$g_{15} = 1 - \frac{\bar{N}\; E_1'/(t_1E_1' + t_2E_2')}{F_{1D}} \qquad (2.18)$$

where,

$$F_{1D} = 2\,\frac{E_1'}{\lambda_1}\left(\frac{t_1}{s}\right)^2$$

$$\lambda_1 = 1 - \nu^2.$$

16. Dimpling of Face 2 - Honeycomb Core

$$g_{16} = 1 - \frac{\bar{N}\; E_2'/(t_1E_1' + t_2E_2')}{F_{2D}} \qquad (2.19)$$

17. Panel Buckling

$$g_{17} = 1 - \frac{\bar{N}}{N_B} \qquad (2.20)$$

where,

N_B = (Critical buckling load from Chapter 5, Reference 6)

18. Panel Buckling - Loading in Two Directions

$$g_{18} = 1 - \frac{\bar{N}_x}{N_{xB}} - \frac{\bar{N}_y}{N_{yB}} \qquad (2.21)$$

where,

N_{xB}, N_{yB} = (Critical buckling loads acting individually)

Not all of the constraints will necessarily be used for a particular design problem. For example, if the thickness of Face 1 is not taken as a design variable then g_1 would not be used. In the case of multiple loading conditions, multiple sets of constraints 9-18 are necessary.

The constraint functions have been designed so that:

(a) a positive value indicates a design point in the acceptable portion of the design space,

(b) a negative value indicates a design point in the unacceptable region, and

(c) a positive value near zero indicates a design point on the boundary of the acceptable region.

SECTION 3
IMPLEMENTATION

This section contains information concerning the computer program which implements the procedure, presented in Section 2, for designing sandwich panels for minimum weight. The computer program SANOPT is operational on the ASD CYBER computers at Wright-Patterson Air Force Base. The FORTRAN source code (Appendix B) is resident on the ASD permanent disc storage files. The present version of the program is intended for interactive usage through remote terminals via INTERCOM. The program operates interactively, and executes entirely in-core. 21,320 octal words of central memory are required to load, and 37,700 octal words are necessary for execution.

3.1 PROGRAM ORGANIZATION

SANOPT is organized in overlay format with one main overlay and five primary overlays. The overlay structure is as follows:

OVERLAY LEVEL	OVERLAY NAME	OVERLAY FUNCTION
(0.0)	SANOPT	Main overlay and program driver. Contains the field interactive input data reader. Reads in control information, data to start the problem and directs calls to the primary overlays.
(0.1)	LONGER	Primary overlay to read input data and initialize design parameters. The parameters along with their description are printed out on the user terminal.
(2.0)	SHORT	Primary overlay same as above, but only the parameter names without their description are printed out on the user terminal.
(3.0)	SUMT	Primary overlay, contains the program for sequential unconstrained

minimization algorithm (see Reference 7 for details).

(4.0)	OUTPUT	Primary overlay contains statements used to print out information on the results of the optimization problem.
(5.0)	ALTER	Primary overlay contains input data reader. It allows the user to change any data read in the overlays LONGER or SHORT.

3.2 INPUT VARIABLES

The following describes the quantities which are requested interactively by SANOPT:

VARIABLE	DEFINITION
FCT	Type of Core = Y: Honeycomb = N: Foam
TPE	Type of Cell for Honeycomb Core = H: Hexagon = S: Square
FI	Type of Face Panels = Y: Isotropic = N: Orthotropic
LTP	Load Type = 1: Edgewise compression in X-direction = 2: Edgewise compression in Y-direction = 3: Edgewise shear = 4: Edge moment in X-direction = 5: Edge moment in Y-direction = 6: Transverse shear in X-direction = 7: Transverse shear in Y-direction = 8: Transverse normal load = 9: Combined loads =10: Multiple loads (Types 3-10 are not active)
IED	Panel Edge Conditions = 1: All edges simply supported = 2: X-direction clamped = 3: Y-direction clamped = 4: All edges clamped

AA	Edge Dimension in X-Direction
BB	Edge Dimension in Y-Direction
XNBAR	Applied load
NLT	Number of different load types
LC	Load type
N	Number of design variables
T1,T2	Thickness of face panels
TC	Thickness of core
RHOC	Density of foam
S	Size of cell for honeycomb core
TF	Thickness of foil for honeycomb core
IDV	Design variable code
D	Thickness of sandwich panel
RHO,RHOF	Density of foil for honeycomb core
RHOC	Density of foam
E	Young's Modulus of core
F	Compressive strength of core
GO	Transverse shear modulus of core
R	Ratio G_{cx} and G_{cy} of the core
Ej,Ejx,Ejy	Young's moduli for face j
PRjX,PRjY	Poisson's ratio for face j
Gyxj	Shear modulus for face j
RHOj	Density of face j
YIELDj	Compressive yield stress
DFj	Deflection waviness of face j

3.3 SAMPLE TERMINAL SESSION

The input variables defined in Paragraph 3.2 are input interactively by the user of SANOPT in response to prompts by the program. The format of the prompts, together with the variable definitions in the previous paragraph, make the data input largely self-explanatory. This paragraph contains a discussion of a sample terminal session which illustrates the use of SANOPT to determine the particular configuration of a sandwich panel which has minimum weight.

The objective of the design session is to select the thicknesses of the two faces, the thickness of the hexagonal honeycomb core, the honeycomb cell size, and the honeycomb foil thickness of a sandwich panel with characteristics as shown in Figure 4. The simply supported panel has planform dimensions of 80 inches by 40 inches and is subjected to an in-plane compressive load of 1000 lb/in on the 40 inch side. The upper and lower face sheets are aluminum with Young's modulus 30 x 10^6 psi, Poisson's ratio .25, and weight density .1 lb/in^3. The core is to be an aerospace grade 5052 alloy hexagonal aluminum honeycomb selected from Figure 5.

Figures 6a-l contain a sample interactive session with the SANOPT sandwich panel optimization program. In the sample session the printouts which have not been underlined are either informative comments or prompts which require some action by the user: the underlined printouts are the responses by the user to the various prompts. Each of the Figures 6a-l are considered in turn below:

(a) Figure 6a

The "LOGIN" procedure and the program access routine are illustrated in Figure 6a. After the computer (the ASD CDC system) responds to the telephone dialup by identifying the system, the date, and the time, the user responds to a series of prompts by typing "LOGIN", a valid problem number, a password, and a terminal identification number. The login process is then

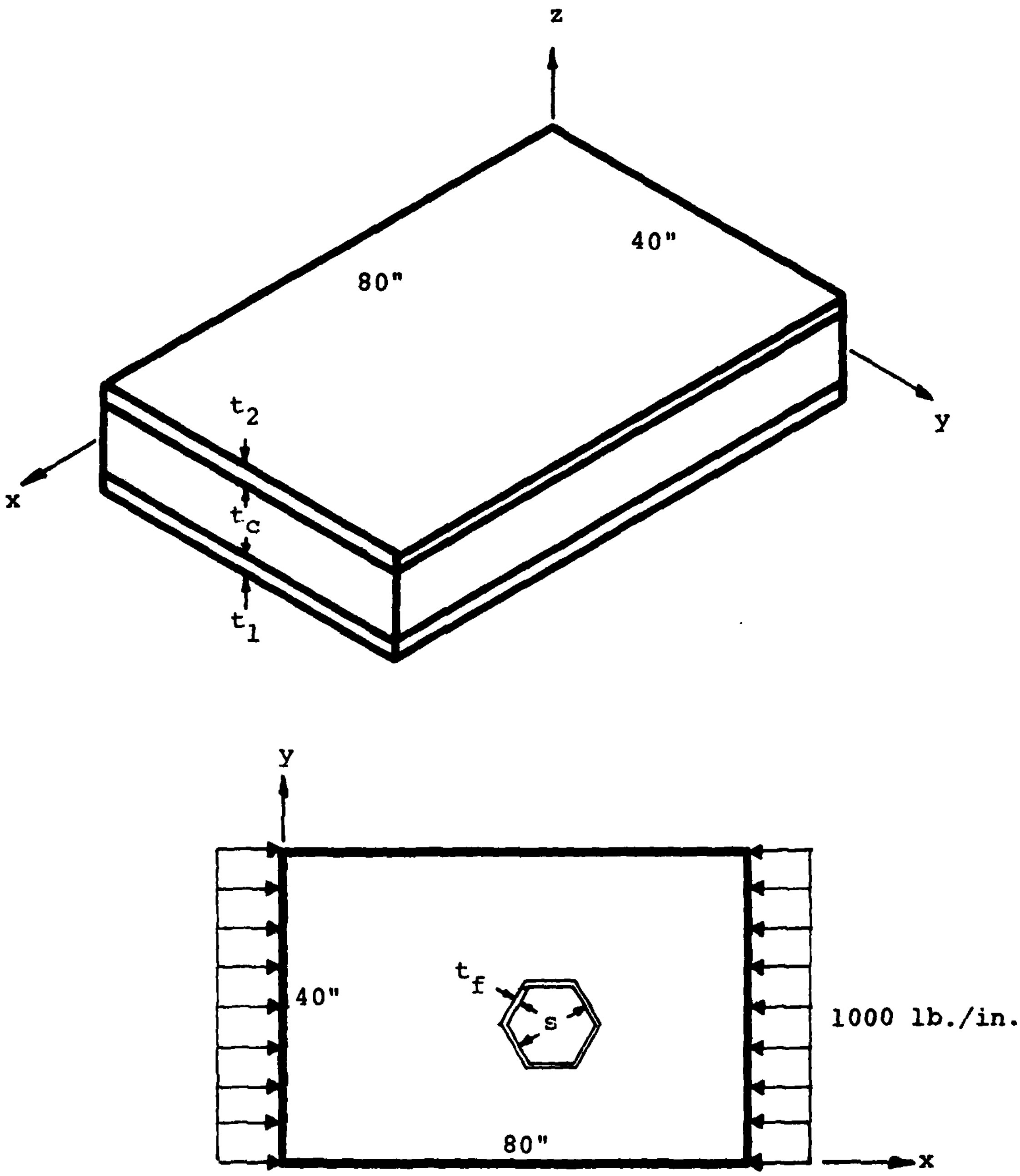

Figure 4. Sandwich Panel Design Example.

5052 ALLOY HEXAGONAL ALUMINUM HONEYCOMB

AEROSPACE GRADE

HEXCEL HONEYCOMB DESIGNATION Cell-Material-Gage	Nominal Density pcf	COMPRESSIVE Bare Strength psi		COMPRESSIVE Stabilized Strength psi		Stabilized Modulus ksi	Crush Strength psi	PLATE SHEAR "L" Direction Strength psi		"L" Direction Modulus ksi	PLATE SHEAR "W" Direction Strength psi		"W" Direction Modulus ksi
		typ	min	typ	min	typical	typ	typ	min	typical	typ	min	typical
1/8-5052-.0007	**3.1**	**270**	**200**	**290**	**215**	**75**	**130**	**210**	**155**	**45.0**	**130**	**90**	**22.0**
1/8-5052-.001	**4.5**	**520**	**375**	**545**	**405**	**150**	**260**	**340**	**285**	**70.0**	**220**	**168**	**31.0**
1/8-5052-.0015	**6.1**	**870**	**650**	**910**	**680**	**240**	**450**	**505**	**455**	**98.0**	**320**	**272**	**41.0**
1/8-5052-.002	**8.1**	**1400**	**1000**	**1470**	**1100**	**350**	**750**	**725**	**670**	**135**	**455**	**400**	**54.0**
1/8-5052-.003	12.0	2200P	—	2325P	—	900P	—	1100P	—	—	625	—	—
5/32-5052-.0007	2.6	200	150	215	160	55	90	165	120	37.0	100	70	19.0
5/32-5052-.001	3.8	395	285	410	300	110	185	270	215	56.0	175	125	26.4
5/32-5052-.0015	5.3	690	490	720	535	195	340	420	370	84.0	270	215	36.0
5/32-5052-.002	6.9	1080	770	1130	800	285	575	590	540	114	375	328	46.4
5/32-5052-.0025	8.4	1530	1070	1600	1180	370	800	760	690	140	475	420	56.0
3/16-5052-.0007	2.0	130	90	135	100	34	60	120	80	27.0	70	46	14.3
3/16-5052-.001	**3.1**	**270**	**200**	**290**	**215**	**75**	**130**	**210**	**155**	**45.0**	**130**	**90**	**22.0**
3/16-5052-.0015	**4.4**	**500**	**360**	**525**	**385**	**145**	**250**	**330**	**280**	**68.0**	**215**	**160**	**30.0**
3/16-5052-.002	**5.7**	**770**	**560**	**810**	**600**	**220**	**390**	**460**	**410**	**90.0**	**300**	**244**	**38.5**
3/16-5052-.0025	6.9	1080	770	1130	800	285	575	590	540	114	375	328	46.4
3/16-5052-.003	8.1	1400	1000	1470	1100	350	750	725	670	135	455	400	54.0
1/4-5052-.0007	1.6	85	60	95	70	20	40	85	60	21.0	50	32	11.0
1/4-5052-.001	**2.3**	**165**	**120**	**175**	**130**	**45**	**75**	**140**	**100**	**32.0**	**85**	**57**	**16.2**
1/4-5052-.0015	**3.4**	**320**	**240**	**340**	**250**	**90**	**150**	**235**	**180**	**50.0**	**150**	**105**	**24.0**
1/4-5052-.002	**4.3**	**480**	**350**	**505**	**370**	**140**	**230**	**320**	**265**	**66.0**	**210**	**155**	**29.8**
1/4-5052-.0025	5.2	670	500	690	510	190	335	410	360	82.0	265	200	35.4
1/4-5052-.003	6.0	850	630	880	660	235	430	495	445	96.0	315	265	40.5
1/4-5052-.004	**7.9**	**1360**	**970**	**1420**	**1050**	**340**	**725**	**700**	**650**	**130**	**440**	**390**	**52.8**
3/8-5052-.0007	1.0	30	20	45	20	10	25	45	32	12.0	30	20	7.0
3/8-5052-.001	1.6	85	60	95	70	20	40	85	60	21.0	50	32	11.0
3/8-5052-.0015	2.3	165	120	175	130	45	75	140	100	32.0	85	57	16.2
3/8-5052-.002	3.0	260	190	270	200	70	120	200	145	43.0	125	85	21.2
3/8-5052-.0025	3.7	370	270	390	285	105	180	260	200	55.0	170	115	26.0
3/8-5052-.003	4.2	460	335	485	355	135	220	310	255	65.0	200	150	29.0
3/8-5052-.004	5.4	720	500	745	535	200	360	430	380	86.0	280	228	36.8
3/8-5052-.005	**6.5**	**970**	**700**	**1020**	**750**	**265**	**505**	**545**	**500**	**105**	**350**	**300**	**43.5**

Figure 5. Sample Honeycomb Data.

```
ASD COMPUTER CENTER INTERCOM 5.0
SYSTEM  CSA
DATE  12/05/80        TIME  12.01.05.

PLEASE LOGIN
LOGIN
ENTER PROBLEM NUMBER-_________
[redacted] ENTER PASSWORD-
ENTER 3-DIGIT TERMINAL ID-____

12/05/80   LOGGED IN AT  12.01.46.
           WITH USER-ID WH
           EQUIP/PORT 16/017

LOGIN       CREATED 12/05/80  TODAY IS 12/05/80


COMMAND- ATTACH,P,SANOPT,CY=1,ID=SONI,SN=AFFDL
COMMAND- FTN,I=P,L=PR,B=LGO
     7.678 CP SECONDS COMPILATION TIME
COMMAND- LGO


     FOLLOWING IS THE MOST RECENT
  VERSION OF THE SANDWICH PANEL
  OPTIMIZATION PROGRAM USED TO COMPUTE
  THE MINIMUM WEIGHT OF A SANDWICH
  PANEL REQUIRING SEVERAL DESIGN
  VARIABLES.
     AS OF NEW THE PROGRAM IS SET UP
  TO OPTIMIZE SANDWICH PANELS WITH
  EITHER A FOAM OR HONEYCOMB CORE WITH
  AN EDGEWISE COMPRESSIVE LOAD IN THE
  X-DIRECTION OR Y-DIRECTION.
     THE PROGRAM WILL BE MODIFIED TO
  ACCOMODATE OTHER CONDITIONS.
  (   JULY 15, 1980) U.D.R.I.
```

Figure 6a. LOGIN and Program Entry.

```
*********** SANDWICH PANEL OPTIMIZATION PROGRAM ***********
IS THE LONG FORM OF THE INPUT DESIRED(Y-YES,N-NO)? --------: Y
IS A HONEYCOMB CORE DESIRED(Y-YES,N-NO)? ------------------: Y
IS A HEXAGON OR SQUARE CELL DESIRED(H,S)? -----------------: H
ARE ISOTROPIC FACES DESIRED(Y-YES,N-NO)? ------------------: Y
**************** LOAD AND EDGE CONDITIONS ****************
ENTER LOAD TYPE DESIRED
    1-EDGEWISE COMPRESSION X-DIR
    2-EDGEWISE COMPRESSION Y-DIR

NUMBER--------------------------------------------------: 1
ENTER THE PANEL EDGE CONDITIONS
    1-ALL EDGES SIMPLE SUPPORT
    2-X-DIR CLAMPED, Y-DIR SIMPLE SUPPORT
    3-X-DIR SIMPLE SUPPORT, Y-DIR CLAMPED
    4-ALL EDGES CLAMPED
NUMBER----------------------------------------------------: 1
ENTER THE EDGE DIMENSION IN THE X-DIR --------------------: 60
ENTER THE EDGE DIMENSION IN THE Y-DIR --------------------: 40
ENTER THE APPLIED LOAD(LB/IN) ----------------------------: 1000
********************** DESIGN VARIABLES *******************
THE DESIGN VARIABLES FOR THE PANEL ARE AS FOLLOWS:
1-T1  2-T2  3-TC  4-S  5-TF
ENTER THE NUMBER OF DESIGN VARIABLES AND
DESIGN VARIABLE CODES IN ASCENDING ORDER -----------------: 5 1 2 3 4 5
ENTER THE INITIAL VALUES OF THE DESIGN VARIABLES
    1-T1  2-T2  3-TC  4-S  5-TF
------------------------------------------------: .01 .01 .75 .25 .001
ENTER THE MINIMUM VALUE FOR T1 ---------------------------: .005
ENTER THE MINIMUM VALUE FOR T2 ---------------------------: .005
ENTER THE MINIMUM VALUE FOR TC ---------------------------: .1
ENTER THE MINIMUM AND MAXIMUM VALUE FOR S ----------------: .125 .375
ENTER THE MINIMUM VALUE FOR TF ---------------------------: .0007
ENTER THE MAXIMUM THICKNESS OF THE SANDWICH PANEL---------: 1.5
********************** CORE PROPERTIES ********************
ENTER THE DENSITY OF THE FOIL ----------------------------: .1
ENTER THE MODULUS OF THE CORE ----------------------------: 75E3
ENTER THE COMPRESSIVE STRENGTH OF THE CORE ---------------: 290
ENTER THE TRANSVERSE SHEAR MODULUS OF THE CORE -----------: 45E3
ENTER THE RATIO GCX/GCY OF THE CORE ----------------------: 2.04
******************** FACE 1 PROPERTIES *******************
ENTER YOUNG'S MODULUS OF THE FACE ------------------------: 10E6
ENTER POISSON'S RATIO OF THE FACE ------------------------: .25
ENTER THE DENSITY OF THE FACE ----------------------------: .1
ENTER THE COMPRESSIVE      YIELD STRESS OF THE FACE -----: 50000
ENTER THE DEFLECTION WAVINESS OF THE FACE ----------------: .001
******************** FACE 2 PROPERTIES *******************
ENTER YOUNG'S MODULUS OF THE FACE ------------------------: 10E6
ENTER POISSON'S RATIO OF THE FACE ------------------------: .25
ENTER THE DENSITY OF THE FACE ----------------------------: .1
ENTER THE COMPRESSIVE      YIELD STRESS OF THE FACE -----: 50000
ENTER THE DEFLECTION WAVINESS OF THE FACE ----------------: .001
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: N
```

Figure 6b. Input Data for Initial Design Iteration.

```
******************** OPTIMIZATION BEGINS *******************

                        PANEL NO.   1

***************** OPTIMIZED SANDWICH PANEL ****************
                    DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE --------------:      .024897
THE THICKNESS OF FACE 2 SHOULD BE --------------:      .024897
THE THICKNESS OF THE CORE SHOULD BE ------------:     1.042736
THE CELL SIZE OF THE CORE SHOULD BE ------------:      .245888
THE THICKNESS OF THE FOIL SHOULD BE ------------:      .004147


THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:   30.939994 LBS


THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS             .39794352E+01
   MINIMUM FACE 2 THICKNESS             .39794326E+01
   MAXIMUM SANDWICH THICKNESS           .27164630E+00
   MINIMUM CORE THICKNESS               .94273621E+01
   COMPRESSIVE YIELD FACE 1             .59834792E+00
   COMPRESSIVE YIELD FACE 2             .59834792E+00
   MINIMUM FOIL THICKNESS               .49238681E+01
   MINIMUM CELL SIZE                    .96710371E+00
   WRINKLING FACE 1                     .74174157E-06
   WRINKLING FACE 2                     .21017850E-06
   DIMPLING FACE 1                      .90818034E+00
   DIMPLING FACE 2                      .90818024E+00
   BUCKLING LOAD                        .11335903E-06
   MAXIMUM CELL SIZE                    .52508482E+00
```

Figure 6c. Initial Trial Design.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? -------: Y
1-TYPE OF HONEYCOMB CORE
2-EDGE CONDITIONS
3-DIMENSION X-DIR
4-DIMENSION Y-DIR
5-APPLIED LOAD
6-INITIAL VALUES
7-MINIMUM T1
8-MINIMUM T2
9-MINIMUM TC
10-MINIMUM RHOC(FOAM)
11-MINIMUM S(HONEYCOMB)
12-MAXIMUM S(HONEYCOMB)
13-MINIMUM TF(HONEYCOMB)
14-T1
15-T2
16-TC
17-RHOC(FOAM)
18-S(HONEYCOMB)
19-TF(HONEYCOMB)
20-CORE MATERIAL DENSITY
21-CORE MODULUS
22-CORE COMPRESSIVE STRENGTH
23-CORE TRANSVERSE SHEAR MODULUS
24-CORE GCX/GCY RATIO
25-YOUNGS MODULUS FACE 1
26-YOUNGS MODULUS FACE 2
27-POISSONS RATIO FACE 1
28-POISSONS RATIO FACE 2
29-FACE 1 DENSITY
30-FACE 2 DENSITY
31-FACE 1 YIELD STRESS
32-FACE 2 YIELD STRESS
33-FACE 1 DEFLECTION
34-FACE 2 DEFLECTION
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST --------------------------------------: 1 6
X(1-N) --------.01 .01 .75 .35 .001
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? ----------------: N
```

Figure 6d. List of Possible Changes and Data for New Starting Point.

```
******************* OPTIMIZATION BEGINS *******************

                    PANEL NO.   2

***************** OPTIMIZED SANDWICH PANEL ****************
                   DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE ---------------:       .024897
THE THICKNESS OF FACE 2 SHOULD BE ---------------:       .024897
THE THICKNESS OF THE CORE SHOULD BE -------------:      1.042746
THE CELL SIZE OF THE CORE SHOULD BE -------------:       .247551
THE THICKNESS OF THE FOIL SHOULD BE -------------:       .004175

THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE -----:   30.939993 LBS

THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS                .39794728E+01
   MINIMUM FACE 2 THICKNESS                .39794740E+01
   MAXIMUM SANDWICH THICKNESS              .27163981E+00
   MINIMUM CORE THICKNESS                  .94274554E+01
   COMPRESSIVE YIELD FACE 1                .59835110E+00
   COMPRESSIVE YIELD FACE 2                .59835110E+00
   MINIMUM FOIL THICKNESS                  .49638305E+01
   MINIMUM CELL SIZE                       .98040829E+00
   WRINKLING FACE 1                        .23058593E-06
   WRINKLING FACE 2                        .48491061E-06
   DIMPLING FACE 1                         .90693623E+00
   DIMPLING FACE 2                         .90693628E+00
   BUCKLING LOAD                           .94919045E-07
   MAXIMUM CELL SIZE                       .51483915E+00
```

Figure 6e. Initial Trial Design Recomputed.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? --------: N
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST -----------------------------------: 1 6
X(1-N) ---------.01 .01 .25 .25 .001
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? -----------------: N
******************* OPTIMIZATION BEGINS ******************

                    PANEL NO.  3

***************** OPTIMIZED SANDWICH PANEL ***************
                    DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE ---------------:      .024900
THE THICKNESS OF FACE 2 SHOULD BE ---------------:      .024900
THE THICKNESS OF THE CORE SHOULD BE -------------:     1.042857
THE CELL SIZE OF THE CORE SHOULD BE -------------:      .245885
THE THICKNESS OF THE FOIL SHOULD BE -------------:      .004146

THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:   30.939994 LBS

THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS          .39799470E+01
   MINIMUM FACE 2 THICKNESS          .39799502E+01
   MAXIMUM SANDWICH THICKNESS        .27156223E+00
   MINIMUM CORE THICKNESS            .94285716E+01
   COMPRESSIVE YIELD FACE 1          .59838943E+00
   COMPRESSIVE YIELD FACE 2          .59838943E+00
   MINIMUM FOIL THICKNESS            .49224489E+01
   MINIMUM CELL SIZE                 .96707651E+00
   WRINKLING FACE 1                  .25608122E-06
   WRINKLING FACE 2                  .88910409E-06
   DIMPLING FACE 1                   .90821124E+00
   DIMPLING FACE 2                   .90821136E+00
   BUCKLING LOAD                     .48938553E-07
   MAXIMUM CELL SIZE                 .52510590E+00
```

Figure 6f. Data for New Starting Point and Recomputed Initial Trial Design.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? -------: N
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST -----------------------------------: 4 21 22 23 24
E --------------340E3
F --------------1420
GG -------------130E3
R ---------------2.44
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? ------------------: N
******************** OPTIMIZATION BEGINS ******************

                          PANEL NO.   4

***************** OPTIMIZED SANDWICH PANEL ****************
                         DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE ----------------:        .018355
THE THICKNESS OF FACE 2 SHOULD BE ------- --------:        .018355
THE THICKNESS OF THE CORE SHOULD BE --------- ----:        .957180
THE CELL SIZE OF THE CORE SHOULD BE --------- ----:        .235426
THE THICKNESS OF THE FOIL SHOULD BE ---------- --.         .002011

THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:    18.724312 LBS

THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS              .26710706E+01
   MINIMUM FACE 2 THICKNESS              .26710696E+01
   MAXIMUM SANDWICH THICKNESS            .33740614E+00
   MINIMUM CORE THICKNESS                .85713009E+01
   COMPRESSIVE YIELD FACE 1              .45519973E+00
   COMPRESSIVE YIELD FACE 2              .45519970E+00
   MINIMUM FOIL THICKNESS                .18728077E+01
   MINIMUM CELL SIZE                     .88341166E+00
   WRINKLING FACE 1                      .79147711E-06
   WRINKLING FACE 2                      .51289031E-06
   DIMPLING FACE 1                       .78994470E+00
   DIMPLING FACE 2                       .78994458E+00
   BUCKLING LOAD                         .79789196E-07
   MAXIMUM CELL SIZE                     .59285411E+00
```

Figure 6g. Change Data for 1/4 - 5052 - .004 Core and Associated Design Results.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? ------------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? --------: N
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST ---------------------------------------------: 4 21 22 23 24
E ---------------140E3
F ---------------500
GO --------------66E3
R ---------------2.22
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? ------------------: N
******************* OPTIMIZATION BEGINS *******************

                        PANEL NO.  5

***************** OPTIMIZED SANDWICH PANEL ***************
                      DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE ---------------:      .022106
THE THICKNESS OF FACE 2 SHOULD BE ---------------:      .022106
THE THICKNESS OF THE CORE SHOULD BE -------------:     1.010501
THE CELL SIZE OF THE CORE SHOULD BE -------------:      .241586
THE THICKNESS OF THE FOIL SHOULD BE -------------:      .003128

THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:   25.374446 LBS

THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS             .34271442E+01
   MINIMUM FACE 2 THICKNESS             .34271503E+01
   MAXIMUM SANDWICH THICKNESS           .29143191E+00
   MINIMUM CORE THICKNESS               .91858067E-01
   COMPRESSIVE YIELD FACE 1             .54824182E+00
   COMPRESSIVE YIELD FACE 2             .54824182E+00
   MINIMUM FOIL THICKNESS               .34685399E+01
   MINIMUM CELL SIZE                    .94069993E+00
   WRINKLING FACE 1                     .19472559E-06
   WRINKLING FACE 2                     .15587763E-05
   DIMPLING FACE 1                      .87283655E+00
   DIMPLING FACE 2                      .87283690E+00
   BUCKLING LOAD                        .21074239E-06
   MAXIMUM CELL SIZE                    .54584200E+00
```

Figure 6h. Change Data for 1/4 - 5052 - .002 Core and Associated Design Results.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? -------: N
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST -------------------------------------------: 4 21 22 23 24
E ---------------90E3
F ---------------340
GO --------------50E3
R ---------------2.08
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? ----------------: N
******************* OPTIMIZATION BEGINS *******************

                    PANEL NO.  6

***************** OPTIMIZED SANDWICH PANEL ****************
                    DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE --------------:     .024058
THE THICKNESS OF FACE 2 SHOULD BE --------------:     .024058
THE THICKNESS OF THE CORE SHOULD BE ------------:    1.036955
THE CELL SIZE OF THE CORE SHOULD BE ------------:     .249145
THE THICKNESS OF THE FOIL SHOULD BE ------------:     .003890

THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:   29.213107 LBS

THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS          .38116619E+01
   MINIMUM FACE 2 THICKNESS          .38116575E+01
   MAXIMUM SANDWICH THICKNESS        .27661922E+00
   MINIMUM CORE THICKNESS            .93695458E+01
   COMPRESSIVE YIELD FACE 1          .58434300E+00
   COMPRESSIVE YIELD FACE 2          .58434300E+00
   MINIMUM FOIL THICKNESS            .45571513E+01
   MINIMUM CELL SIZE                 .99316288E+00
   WRINKLING FACE 1                  .15994002E-05
   WRINKLING FACE 2                  .68327717E-06
   DIMPLING FACE 1                   .89552274E+00
   DIMPLING FACE 2                   .89552255E+00
   BUCKLING LOAD                     .33754928E-06
   MAXIMUM CELL SIZE                 .50514543E+00
```

Figure 6i. Change Data for 1/4 - 5052 - .0015 Core and Associated Design Results.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: Y
IS A LIST OF POSSIBLE CHANGES DESIRED(Y-YES,N-NO)? -------: N
ENTER THE NUMBER OF CHANGES AND THE CHANGE CODES
FROM THE LIST ------------------------------------------: 4 21 22 23 24
E --------------190E3
F --------------690
GO -------------82E3
R --------------2.31
ARE THERE ANY OTHER CHANGES(Y-YES,N-NO)? -----------------: N
******************** OPTIMIZATION BEGINS ******************


                           PANEL NO.   7

****************** OPTIMIZED SANDWICH PANEL ***************
                         DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE --------------:       .020831
THE THICKNESS OF FACE 2 SHOULD BE --------------:       .020831
THE THICKNESS OF THE CORE SHOULD BE ------------:       .999022
THE CELL SIZE OF THE CORE SHOULD BE ------------:       .240961
THE THICKNESS OF THE FOIL SHOULD BE ------------:       .002705


THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:    22.900492 LBS


THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS            .31661007E+01
   MINIMUM FACE 2 THICKNESS            .31661014E+01
   MAXIMUM SANDWICH THICKNESS          .30621100E+00
   MINIMUM CORE THICKNESS              .89902248E+01
   COMPRESSIVE YIELD FACE 1            .51993483E+00
   COMPRESSIVE YIELD FACE 2            .51993483E+00
   MINIMUM FOIL THICKNESS              .28638435E+01
   MINIMUM CELL SIZE                   .92768639E+00
   WRINKLING FACE 1                    .36941077E-06
   WRINKLING FACE 2                    .53460600E-06
   DIMPLING FACE 1                     .84944169E+00
   DIMPLING FACE 2                     .84944174E+00
   BUCKLING LOAD                       .16076324E-06
   MAXIMUM CELL SIZE                   .55626974E+00
```

Figure 6j. Change Data for 1/4 - 5052 - .0025 Core and Associated Design Results.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: N
IS A NEW PROBLEM DESIRED(Y-YES,N-NO)? ----------------------: Y
IS THE LONG FORM OF THE INPUT DESIRED(Y-YES,N-NO)? --------: N
FCT,FI ----------Y Y
TFE -------------H
LTF,IED,AA,BB -1 1 80 40
XNBAR(   1) -----1000
N,IDV(1-N) ----3 1 2 3
X(1-N) ----------.02 .02 1
T1MIN -----------.005
T2MIN -----------.005
TCMIN -----------.1
DMAX ------------1.5
RHO,E,F,GO,R --.1 190E3
690 82E3 2.31
S ---------------.25
TF --------------.0025
E1,E2,PR1,PR2,RHO1,RHO2,DF1,DF2 --10E6 10E6 .25 .25 .1 .1 .001 .001
COMPRESSIVE        STRESS YIELD1,YIELD2 --50000 50000
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? ------------: N
******************** OPTIMIZATION BEGINS ********************


                          PANEL NO.  8


****************** OPTIMIZED SANDWICH PANEL *****************
                      DESIGN PARAMETERS

THE THICKNESS OF FACE 1 SHOULD BE ---------------:      .021904
THE THICKNESS OF FACE 2 SHOULD BE ---------------:      .021904
THE THICKNESS OF THE CORE SHOULD BE ------------:     1.050190


THE ABOVE VALUES OF THE DESIGN PARAMETERS YIELDS
A MINIMUM WEIGHT FOR THE SANDWICH PANEL TO BE ----:    22.980527 LBS


THE FINAL CONSTRAINT VALUES ARE:
   MINIMUM FACE 1 THICKNESS          .33808869E+01
   MINIMUM FACE 2 THICKNESS          .33808077E+01
   MAXIMUM SANDWICH THICKNESS        .27066224E+00
   MINIMUM CORE THICKNESS            .95019776E+01
   COMPRESSIVE YIELD FACE 1          .54347148E+00
   COMPRESSIVE YIELD FACE 2          .54347148E+00
   WRINKLING FACE 1                  .29666614E-06
   WRINKLING FACE 2                  .46893691E-06
   DIMPLING FACE 1                   .86062171E+00
   DIMPLING FACE 2                   .86062176E+00
   BUCKLING LOAD                     .82491468E-07
```

Figure 6k. Short Form of Data Input, Fixing the Core Properties, and Final Design Results.

```
ARE THERE ANY CHANGES TO THE DATA(Y-YES,N-NO)? -----------: N
IS A NEW PROBLEM DESIRED(Y-YES,N-NO)? --------------------: N
     STOP
     037700 MAXIMUM EXECUTION FL.
     12.039 CP SECONDS EXECUTION TIME.
COMMAND- LOGOUT
CPA      20.283 SEC.         16.529 ADJ.
IO       54.409 SEC.         16.104 ADJ.
CRUS                         39.359
CONNECT TIME     0 HRS.    19 MIN.
 11/21/80  LOGGED OUT AT 12.19.55.
```

Figure 6k. (concluded).

complete. A series of commands is then issued to retrieve the FORTRAN source code from permanent file storage, to compile the source code and create a binary deck, and to execute the created binary code. A printed message indicates that the SANOPT program has been entered successfully, and an interactive design session has been initiated.

(b) Figure 6b

Figure 6b contains a series of program prompts and user responses to define completely an initial panel optimization problem. The data are input in seven distinct sets as designated below:

1. General Data

The first group of input data prompts and responses is a series of questions which have non-numerical responses. There are two forms of data input, the long form and the short form. In the case of the long form, the prompts are self-explanatory. The short form generally takes less time for data input, but the prompts are brief, with the data required being identified only by the variable names of Paragraph 3.2. The long form is requested here; the short form will be considered later. A honeycomb type core with hexagonal cells is specified and the faces are identified to be isotropic.

2. Loading and Edge Conditions

The load type is specified to be an edgewise compressive load on the x-edges of the panel, the panel is simply-supported all around, the planform dimensions are 80" x 40", and the applied edgewise compression load is 1000 lb/in.

3. Design Variable Data

The possible sandwich panel design variables are defined in Paragraph 2.4. In the case of honeycomb core these are: the thickness of face 1 (T1), the thickness of face 2 (T2), the depth of the core (TC), the honeycomb cell size (S), and the honeycomb foil thickness (TF). The user is free to define any or all of these possible design variables as the actual design variables. In this case all five of the possibilities are selected as design variables. The initial values of the design variables define a point in the multi-dimensional design space from which the optimization process will start. The parameters in those constraints which apply directly to the design variables (see Paragraph 2.6) are then defined by specifying minimum and/or maximum values of the design variables. Here the minimum gage of the faces is taken to be .005" the minimum core thickness is .1", the minimum and maximum cell sizes are 1/8" and 3/8", the minimum foil gage is .0007", and the maximum total sandwich is defined to be 1.5".

4. Core Data

The next set of input data refer to the sandwich core. In our example, the core is aluminum with weight density of .1 lb/in^3. The transverse modulus, compressive strength, shear modulus (in the load direction), and the ratio of the two shear moduli have been taken arbitrarily (for the time being) to correspond to the honeycomb core 1/8 - 5052 - .0007 in Figure 5. These values must be set before the minimization is initiated because they are used in the computation of some of the constraints (Paragraph 2.6). Obviously, the minimum weight core configuration will not in general correspond to the assumed initial core properties. Our procedure will be to determine a minimum weight panel using a core with properties in Figure 5. This will be an iteration process as seen below.

5. Face 1 Data

The next set of data in Figure 6b refers to face 1 properties. In this case, face 1 is an aluminum sheet with modulus of 10 x 10^6 psi, Poisson's Ratio of .25, weight density of .1 lb/in^3, and compressive yield stress of 50,000 psi.

The initial waviness of the face sheets (i.e., the face is not perfectly flat) is .001"; this value is used to calculate the panel wrinkling stress (Chapter 3 of Reference 6) for evaluating the wrinkling constraints.

6. Face 2 Data

This data is the same as that for face 1 since we have identical faces.

7. Data Termination

The final prompt is an inquiry as to whether there are any changes to be made to the data. At this point, the answer would be "Y" if some mistake had been made in entering any of the data in Figure 6b; then the user would be permitted to change any of the data. In this case we choose to accept the input data by answering "N". This causes the SANOPT program to terminate the data input phase and to begin the optimization process.

(c) Figure 6c

This figure presents the results of the panel optimization using the physical data and the initial panel design variables provided in Figure 6b. The final values of the design parameters are indicated as well as the minimum weight computed from the final design parameters. Also given are the values of the various constraint functions (Paragraph 2.6) which apply to this design example. In this case, the final values of the design parameters have been influenced by the wrinkling constraints and the panel buckling constraint. That is, if a panel were built with the calculated design parameters, it would be that acceptable panel with the least weight but would be on the verge of face wrinkling and gross panel buckling.

(d) Figure 6d

This figure indicates the procedure for making one or more changes to the set of data input in Figure 6b. Here we specify that we wish to change data, and request that a listing of all possible changes be presented; in response a list of 34 possible data changes is printed. We specify that a single data change be made, and in particular that the initial values of the design parameters be altered. The particular values of the initial parameter values are then input for the five design variables. An indication that no other data changes are to be made then initiates the optimization process with the new starting point in the design space.

The reason for making the change in the starting point in the design space at this stage of the panel design process is to ensure that a valid minimum weight has been obtained, and not just a relative minimum. Therefore, a new starting point is specified and the minimum weight is recomputed; if the same final values of the design parameters and the same minimum weight are obtained then one can be relatively sure that the proper minimum has been found.

(e) Figure 6e

This figure presents the results of the optimization using the new starting point in the design space. The results are the same as those computed before.

(f) Figure 6f

This figure defines yet another design starting point but this time not requesting a complete listing of the possible changes. The results again are identical to the original problem.

(g) Figure 6g

Although the design computed above represents a valid optimum design for the data input in Figure 6b, the core is not realistic according to what is available commercially. The design on Figure 6c calls for a core with cell size of about 1/4" and a foil thickness of about .004". It is apparent from Figure 5 that no core is available with these dimensions which also has the material properties input in Figure 6b. Therefore, we must try various cores from Figure 5 until we get a minimum design with consistent material properties and geometry.

Figure 6g contains alterations to the data to correspond to core 1/4 - 5052 - 004 in Figure 5. This time the optimized design calls for a core with cell size again 1/4" but with foil thickness of .002". The optimized panel weight is some 12 lb. lighter than the weight of the initial trial design but it is not feasible because there is no core available with the calculated cell size and foil thickness which has the properties specified in Figure 6g.

(h) Figure 6h

Here, guided by the results of the previous trial design, we change the core properties to those of 1/4 - 5052 - .002 in Figure 5. The optimized design for these properties is shown on Figure 6h.

(i) Figure 6i

This figure contains the data changes and the corresponding results for core 1/4 - 5052 - .0015.

(j) Figure 6j

This figure contains the data changes and the corresponding results for core 1/4 - 5052 - .0025.

(k) Figure 6k

The core cell size and foil thickness computed (.240961" and .002705") in Figure 6j are very near the corresponding values for the 1/4 - 5052 - .0025 core whose material properties were input for that trial design. Therefore, we accept the 1/4 - 5052 - .0025 core as the final core to use in the optimum design.

Figure 6k illustrates the use of the short form of the data input in which we specify only three design parameters, the two face thicknesses and the core thickness. The cell size and the foil thickness are preset to .25" and .0025", respectively.

All other data are the same as for the Figure 6j trial design. The final optimized panel design parameters are shown on Figure 6k. In particular, the face thicknesses should be .021904" and the core thickness should be 1.050198" to give an optimized weight of 22.980527 lb.

(1) <u>Figure 6l</u>

This figure illustrates how to exit from the SANOPT program, and the logout procedure.

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

An approach to the optimum design of flat, rectangular sandwich panels subjected to edgewise compression loading has been developed. Using a nonlinear programming method called the Sequential Unconstrained Minimization Technique, the design parameters characteristic of sandwich construction are determined so that the final panel configuration is not just an acceptable design, but is the best acceptable design as far as total panel weight is concerned. The design parameters are the individual thicknesses of the top and bottom face sheets and of the core, the cell size and foil thickness of honeycomb core, and the density of foam core. The acceptable ranges of the design parameters are limited by constraints which ensure, for example, that the thicknesses are within minimum and maximum limits, that the faces do not yield, wrinkle, or dimple, and that the panel does not buckle. Possible panel loads are edgewise compression in two directions.

The computer program which implements the minimum weight sandwich panel design procedure is an easy to use interactive code. Data are entered by the user in response to self-explanatory prompts from the program. The user is offered the opportunity to change data before the optimization procedure is initiated. The results of the minimum weight computations are presented to the user within a few seconds in a concise yet informative format. Typical output data include the optimum values of the design variables, the minimized panel weight, and final values of the design variable constraints.

The results obtained here indicate that the minimum weight design of sandwich panels using an analytical optimization procedure can be effective. The particular panel geometry and loading considered are of limited scope so that the analyses required during the optimization process can be performed using closed form approximate solutions. If the analytical optimization concept is coupled with an efficient finite element analysis procedure, then more complex structural configurations can be considered.

A useful extension to the work presented here would be to integrate the sandwich panel optimization procedure into a multilevel design approach.[8] The multilevel design technique combines the advantages of optimality criteria approaches[9] and of constrained optimization procedures such as the one presented here for the design of sandwich panels. If the multilevel design philosophy were adopted, then for example, complete aircraft wings could be designed for minimum weight. In this case sandwich panels would be only a part of the total structure. It is recommended that an effort be undertaken to extend the existing methodology for optimization of structural sandwich designs to more general structures including sandwich having laminated composite faces, and aircraft wing structures utilizing sandwich components.

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APPENDIX A

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